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Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations

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ABSTRACT

Electricity and heat generation are key contributors to global emissions of greenhouse gases (GHG). In this paper, specific attention is paid to renewable energy technologies (RETs) for electricity and heat generation and reviews current understanding and estimates of life cycle GHG emissions from a range of renewable electricity and heat generation technologies. Comprehensive literature reviews for each RET were carried out. The 79 studies reviewed involved the life cycle assessment (LCA) of renewable electricity and heat generation based on onshore and offshore winds, hydropower, marine technologies (wave power and tidal energy), geothermal, photovoltaic (PV), solar thermal, biomass, waste, and heat pumps. The study demonstrates the variability of existing LCA studies (results) in tracking GHG emissions for electricity and heat generation from RETs. This review has shown that the lowest GHG emissions were associated with offshore wind technologies (mean life cycle GHG emissions could be 5.3–13 g CO_2 eq/kWh). Results compared with GHG estimates by fossil fuel heat and electricity indicated that life cycle GHG emissions are comparatively higher in conventional sources as compared to renewable sources with the exception of nuclear-based power electricity generation. In this present study, considering renewable energy sources, waste treatment and dedicated biomass technologies (DBTs) were found to potentially have high GHG emissions based on the feedstock, selected boundary and the inputs required for their production. The study identifies additional impacts associated with renewable electricity and heat technologies, points out the effectiveness of life cycle analysis (LCA) as a tool for assessing environmental impacts of renewable energy sources and concludes with opportunities for improvement in the future.

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1. Introduction

Renewable energy sources are considered to be those that are primary, clean, low risk, and inexhaustible [1,2]. Renewable energy sources include biomass, hydropower, (shallow and deep) geothermal (i.e., indirect solar energy), solar, wind and marine energies. Nuclear energy is not normally considered to be a renewable energy source as it does not replenish within the lifetime of a person [3]. At the turn of the century, renewable energy sources supplied ∼14% of the total world energy demand [4]; by 2010, this had risen to almost 17% with an estimated 50% of energy demand by 2040 [5].

Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for various products [6]. In order to understand where net savings in GHG emissions can be made, and the magnitude of the opportunities, renewable energy systems can be analysed and compared with the energy systems they would replace [7]. The life cycle analysis/assessment (LCA) method has been widely used to study the environmental burdens of energy produced from various renewable and non-renewable sources [8]. Depending on the scope of the LCA study, life stages of energy production systems may include all or part of (i) fuel production (i.e., to also account for the non-consumable portion of the produced fuel) and transportation to the plant, (ii) facility construction, (iii) facility operation and maintenance, and (iv) dismantling [9]. For example; Hondo [10] developed the life cycle greenhouse gas emissions of nine power generating systems including coal-fired, oil-fired, liquefied natural gas (LNG)-fired, LNG-combined cycle (LNG-CC), nuclear, hydropower, geothermal, wind power and solar photovoltaic (PV). The life stages included (i) plant construction and equipment production, (ii) fuel acquisition, processing, and transportation (in the case of fossil fuels and nuclear), geothermal wells drilling (for both exploration and production wells of the geothermal option), (iii) facility operation, and (iv) storage, disposal, or decommissioning (nuclear) of waste. All the GHG emissions attributed to renewable sources were due to indirect emissions, while for fossil fuel sources, direct CO_2 emissions accounted for the majority of GHG.

This paper reviews current understanding and estimates of life cycle GHG emissions from a range of renewable electricity and heat technologies identified from the Scottish Government's 2020 route map [11] for renewable energy, and discuss potential impacts associated with these emissions. The purpose of this review is therefore two-fold to identify the environmental benefits and impacts associated with renewable electricity and heat technologies; and secondly to assess how life cycle approaches can aid in technology evaluation and selection.

2. Methodology

2.1. Search strategy and study evaluation

This was a purposive review of peer-reviewed literature related to the use of LCA to estimate GHG emissions from renewable energy production technologies. In a few cases, the review was supplemented with literature from web-accessible documents and other grey literature. A computerised search of the following international databases was carried out: BIDS (Joint Information Systems Committee, University of Bath, Bath, UK, www.bids.ac.uk) and ISI Web of Knowledge (Mimas, University of Manchester, UK, wok.mimas.ac.uk). A systematic, staged search strategy was employed using the following search terms: 'biomass' OR 'bioenergy' OR 'energy from waste' OR 'fuel cells' OR 'hydropower' OR 'offshore wind' OR 'onshore wind' OR 'marine' OR 'tidal' OR 'photovoltaic/PV' OR 'geothermal' OR 'solar thermal' OR 'heat pumps' OR 'anaerobic digestion/AD' OR 'biogas' OR 'combined heat and power/CHP' AND 'life cycle analysis/LCA' OR 'greenhouse gas/GHG' OR 'nitrous oxide/N_2O' OR 'methane/CH_4' OR 'carbon dioxide/CO_2'.

2.2. LCA case studies included

In this review almost 9000 references were found. The search was further refined to 197 papers that explicitly estimated the life cycle GHG emissions from the specific renewable energy technologies. Only papers written in English were fully included. Original full texts were obtained for all studies. Upon examination of the full texts, only 102 provided any form of quantitative estimation of lifecycle GHG emissions. Therefore, wider, more descriptive studies and accounts were also included while the following types of studies were excluded (except where a method was used that showed principles relevant to the context of this review): (i) studies that did not provide a whole life cycle (i.e., cradle to grave) estimate of GHG emissions. (ii) Where relevant, studies that did not take land use and management into account as part of the life cycle (a significant contributor to total GHG emissions which is often overlooked). The 85 studies that remained after this filtering process formed the primary basis of this review, although other papers within the database were used as background material. Table 1 provides an overview of the studies reviewed.

2.3. Greenhouse gas emissions

Although there are other environmental emissions (e.g., NO_x and SO_2), this review focuses on emissions of greenhouse gases (GHG), such as CO_2 and CH_4 from renewable energy sources

Table 1
Overview of the technologies considered in the present study.

Renewable technology source	Number of case studies	References
1. Onshore wind	14	[10,21–23,118–129]
2. Offshore wind	5	[20,121–124]
3. Hydro-power	11	[10,14,34,35,122,123,128–130]
4. Marine technologies (Wave & tidal)	4	[36,37,131,132]
5. Geothermal	4	[10,46,123,129]
6. Photovoltaic	19	[10,47,51–54,59–61,122,123,128–130,133–138]
7. Solar thermal	6	[59–61,123]
8. Dedicated biomass	14	[62,65,66,105,123,129,139–142]
9. Waste treatment	4	[122,123,143,144]
10. Heat pumps	4	[97,99,100]
Total	85	

addressed in numerous studies. CO_{2eq}, or carbon dioxide equivalent (CO_{2eq}), is a standard unit for measuring greenhouse gas emissions. The rationale is to express the impact of each different greenhouse gas in terms of the amount of CO_2 that would create the same amount of warming. That way, a carbon footprint consisting of a number of different greenhouse gases can be expressed as a CO_2-equivalent amount [12]. Within the studies used in this review, GHG emissions (gCO_{2eq} kWh_e^{-1}) were generally estimated according to Eq. (1) for the full operational life cycle of each renewable energy source from the manufacturing of the plant to full operation and dismantling of the system (i.e., cradle to grave). For PV and wind energy systems, the majority of emissions are associated with electricity and fuel consumption during manufacturing. In these cases, an average grid mix for the region of manufacturing is typically used to calculate GHG emissions [13].

$$GHG\ emissions = \frac{Total\ CO_2\ emissions\ throughout\ life\ cycle\ (gCO_{2eq})}{Annual\ power\ generation\left(\frac{kWh_e}{yr}\right)lifetime\ (yr)} \quad (1)$$

3. Results

For convenience, result of this review is divided into groups of renewable energy technologies. Every attempt has been made to identify criteria, considerations and assumptions leading to the greenhouse gas estimates for the respective renewable energy technology in the sections below.

3.1. LCA of renewable energy technologies

The LCA can be applied to assess the impact on the environment of electricity and heat generation from renewable energy technologies and will allow producers and policy makers to make better informed decisions pertaining to environmental protection [14]. In LCA, potential environmental impacts associated with the life cycle of a product/service are assessed based on a life cycle inventory (LCI), which includes relevant input/output data and emissions compiled for the system associated with the product/service in question.

3.1.1. Onshore wind

Wind generated electricity is a growing renewable source: the primary energy is free; the generators may be sited on land or offshore; they are relatively environmentally benign; the technology is not overly complex; in many countries good sites for wind farms are not too distant from consumer centres (which is both a plus and a minus because of the social perception of wind farms as noisy and not particularly beautiful; [15]). Costs are competitive

with coal-fired generation, if all lifecycle costs of the latter are taken into account [16]. The installed capacity of wind power has been rapidly increasing during recent years. According to the World Wind Energy Association [17], in 2010 wind power globally generated 430 TWh or about 2.5% of worldwide electricity usage, up from 1.5% in 2008 and 0.1% in 1997. This far exceeds projections made less than 10 years ago, for example in 2006 the World Energy Council estimated that newly installed wind capacity worldwide will reach 180–476 GW by 2020 [18]. In the European Union, the cumulative wind power capacity in 1990 was only 439 MW. This had increased to 34,205 MW by the end of 2004 with significant contributions from Denmark, Germany and Spain [19]. Cumulative installed capacity in the United States gradually grew from nearly zero in the early 1980s to ~3000 MW by 2000, followed by exponential growth over the past decade to more than 35,000 MW in 2009 [20]. A recent review of life cycle GHG emissions from utility-scale onshore wind power installations [20] provides details from 44 separate studies (total of 107 life cycle GHG estimates). Across these studies, mean lifecycle GHG emissions were reported as being 16.0 gCO_{2eq} kWh_e^{-1}, with a range of 1.7–81 gCO_{2eq} kWh_e^{-1}. The current review also identified three further studies not included in the review of Dolan and Heath [20]. The inclusion of these studies [21–23]increased the mean to 34.2 gCO_{2eq} kWh_e^{-1}, and the range to 1.7–123.7 gCO_{2eq} kWh_e^{-1}. The largest contributors to total GHG emissions include the mining of raw materials (~30%), manufacturing of the turbines (~25%), shipping (~10%), and emissions associated with construction such as the excavation of organic-rich soils (~30%). On-going maintenance tended to account for less than 5% of total life cycle GHG emissions [20]. The largest life cycle GHG emission estimates were associated with specific locations that had specific challenges for transportation, where forest had to be cut down to enable construction [24], or where highly organic peat soils had to be excavated [25,26]. The life cycle impact on peat soils will be dependent on how vulnerable that peat is to further erosion over the lifetime of the wind farm, given the changes in hydrology likely to occur as a result of construction on peat [27]. A recent analysis in Scotland, UK has mapped the vulnerability of peat to erosion using five vulnerability classes [28]. By overlaying onshore wind farm developments over the peat vulnerability map, the majority of the installed capacity and pending turbine applications are located on the more vulnerable classes of peat (in particular classes 3 and 4; Fig. 1). This suggests that the majority of wind farm developments in Scotland are likely to have life cycle GHG emissions closer to the higher end of the range of estimates.

Therefore, knowledge regarding the details of the development is very important if selecting life cycle information for use in e.g. a decision making process such as multi-criteria analysis. Table 2 shows an overview of GHG (CO_{2eq}) emissions estimates for onshore wind presented in the literature.

3.1.2. Offshore wind

The number of life cycle GHG emission studies undertaken on offshore wind is much more limited when compared to onshore wind. In a recent review [20], only 12 studies were found that included a total of 16 life cycle GHG estimates. Across these studies, mean lifecycle GHG emissions were reported as being 13.0 ± 5.2 gCO_{2eq} kWh_e^{-1}, with a range of 5.3–24 gCO_{2eq} kWh_e^{-1}. Compared to onshore wind, life cycle GHG emission estimates for offshore wind tend to be lower. To some extent, this is due to economies of scale, with offshore installations tending to be significantly larger than their onshore counterparts. Emissions of GHGs during the construction phase are also thought to be higher in onshore operations as they often require in addition to the mining of raw materials, destruction of forest or peat land habitats; all of which result in significant GHG emissions [20]. However, it should also be noted that the knowledge base for GHG
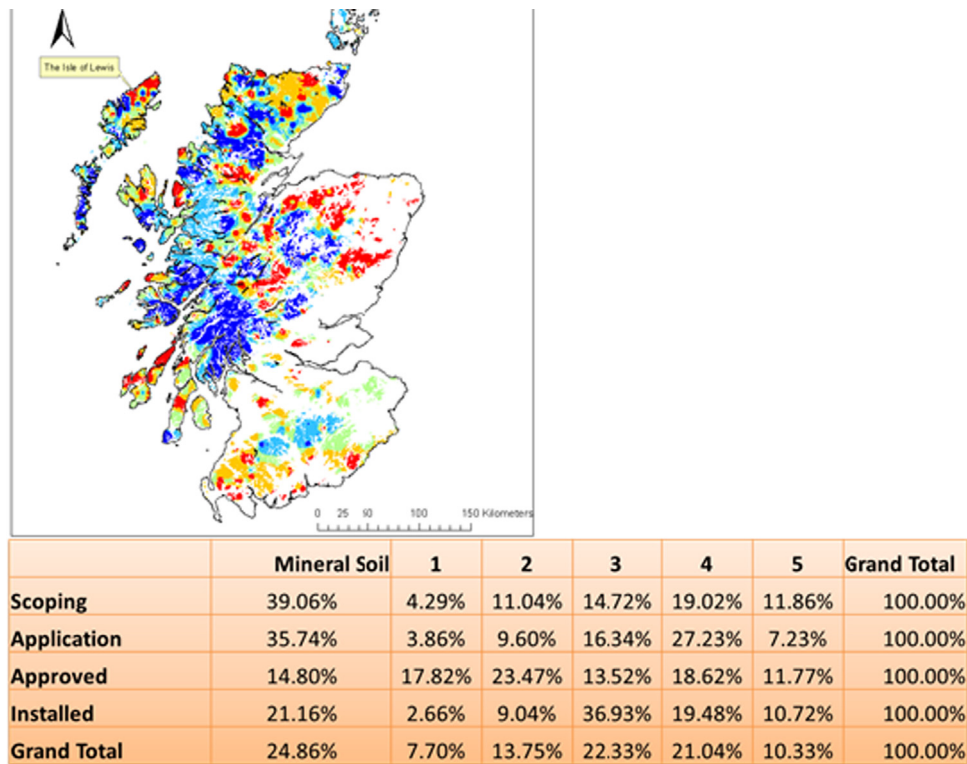
	Mineral Soil	1	2	3	4	5	Grand Total
Scoping	39.06%	4.29%	11.04%	14.72%	19.02%	11.86%	100.00%
Application	35.74%	3.86%	9.60%	16.34%	27.23%	7.23%	100.00%
Approved	14.80%	17.82%	23.47%	13.52%	18.62%	11.77%	100.00%
Installed	21.16%	2.66%	9.04%	36.93%	19.48%	10.72%	100.00%
Grand Total	24.86%	7.70%	13.75%	22.33%	21.04%	10.33%	100.00%

Fig. 1. Vulnerability of peat to erosion in Scotland, UK.

Table 2
Overview of GHG emissions (gCO_{2eq}) of onshore wind.

Study	gCO$_{2eq}$/kWh (Electricity)			Comments
	Mean	**Min**	**Max**	
[21–23,118–120]	34.2	16.5	123.7	
[10]	29.5	15.0	72.0	Base case (300 kW site), small site. Depends on lifetime and capacity factors
[10]	20.3	10.0	49.0	Future (400 kW site), small site. Depends on lifetime and capacity factors
[23]	20.5			
[121]	4.6			Based on LCA for 3 MW turbines
[122]	7.0			
[123]	11.0			German estimates based on dynamic LCA for 1.5 MW turbine
[130]	11.0			Swiss/European average estimate for 800 kW turbine
[125]	14.8	8.8	18.5	Italian estimate for 11 turbines of 600 kW each
[126]		7.9	123.7	Review of LCA estimates for wind (includes both onshore and offshore)
[127]	15.8	12.1	21.2	For 4 MW turbine
[127]	46.4	35.8	58.8	For 250 W turbine
[128]	21.0	13.0	40.0	
[129]	17.7			

Table 3
Overview of GHG emissions (gCO_{2eq}) of offshore wind.

Study	gCO$_{2eq}$/kWh (Electricity)			Comments
	Mean	**Min**	**Max**	
[121]	5.3			Based on LCA for 3 MW turbines
[122]	7.0			
[130]	13.0			For 2 MW turbine in Denmark
[20]		5.3	24	–
[123]	9.0			German estimates for 2.5 MW turbine

emissions associated with offshore turbine construction is much more limited than that for the onshore installations which may lead to considerable underestimation of life cycle GHG emissions [29]. Offshore turbine installations still require raw materials to be mined, turbine bases are larger and require more raw materials compared to onshore, and there are significant demands for shipping. Table 3 shows an overview of estimates of GHG (CO_{2eq}) emissions of offshore wind.

3.1.3. Hydropower

Hydropower is based on a simple process taking advantage of the kinetic energy released by falling water. In all hydroelectric generating stations, the rushing water drives a turbine, which converts the water's motion into mechanical and electrical energy [30]. Globally, hydropower generation is expected to increase from 1953 TWh in 1984 to about 7680 TWh by 2020, a major portion of this growth is expected to take place in developing countries [31]. Globally, hydropower generates more electricity than any other renewable resource and supplied an estimated 3400 TWh

Table 4
Overview of GHG emissions (gCO_{2eq}) of hydro-power.

Study	gCO$_{2eq}$/kWh (Electricity)			Comments
	Mean	Min	Max	
	Mean	Min	Max	
[14,34,35]	45.9	18	74.9	From run-of-river schemes
[14]	15			Estimate in cold climates
[34]	37.4	33.9	43	From canal based schemes
[34]	46.8	31.2	62.4	From dam toe system
[10]	11.3	5	30	From run-of-river type with a small reservoir. Depends on lifetime and capacity factors
[142]		2	15	Review. Values for river run-of and hydro with reservoir, respectively
[130]	4			
[122]	24			
[123]		10	13	German estimates for 300 kW and 3.1 MW run-of-river plant
[128]	15	6.5	44	
[129]	22.7			

Table 5
Overview of GHG emissions (gCO_{2eq}) from marine technologies.

Marine technology	Study	gCO$_{2eq}$/kWh$_e$			Comments
		Mean	Min	Max	
Wave power	[36]		25	50	Reported as an LCA estimate but may only consider CO_2
Wave power	[37]	22.8	12	39	Recycling for disposal
Tidal power	[131]	15	10	20	Recycling for disposal
Tidal power	[132]		20	50	Barrage and lagoon type of plants

during 2011 corresponding to about 15% of the global electricity demand [32]. Despite the scale of the electricity outputs afforded to hydropower, full life cycle estimates of GHG emissions from hydropower are scarce. This review found 11 different studies that reported full life cycle GHG emission estimates (Table 4). These ranged from 2 gCO_{2eq} kWh_e^{-1} to 60 gCO_{2eq} kWh_e^{-1}, with a mean of 20 gCO_{2eq} kWh_e^{-1}. Gagnon and Vate [33] report on the findings of an International Atomic Energy Agency (IAEA) expert meeting on the assessment of GHG emissions from the full life cycle of hydro power. They identify three main sources of life cycle GHG emissions those associated with the construction of the plant; those from decaying biomass from the land flooded by associated reservoirs; and those associated with the thermal back-up power (supplementary electricity generation in cases of seasonal hydro power plants)[1]. Run-of river schemes tend to have significantly more GHG emissions associated with back-up power. This is primarily due to the seasonality of electricity supply. However, overall, run-of-river schemes tend to have lower life cycle GHG emissions in comparison to reservoir-based schemes [34]. This is because reservoir schemes have much greater GHG emissions associated with dam construction (mining, steel, and concrete) and as a result of flooding vegetated land. The site-specific aspects of construction activities results in a substantial range of GHG estimates (1–10 gCO_{2eq} kWh_e^{-1}; [13]). Many factors can affect the rate of GHG emissions from decaying biomass including the amount of biomass per ha prior to flooding, and the size of the flooded area. If worst-case assumptions are made (i.e., 100% of the flooded biomass decomposes over 100 years, and that 20% of biomass carbon would be emitted as CH_4) then the emission factor would be 237 gCO_{2eq} kWh_e^{-1} [33].

3.1.3.1. Small hydropower systems. There is no international consensus on the definition of small hydropower (SHP). The general practice is to define SHP by power output, with the upper limit varying from 5 to 50 MW [13,34]. Small hydropower can be broadly categorised into three different types of scheme, namely; run-of river, canal based, and dam-toe. Emissions of GHGs from run-of river schemes have been estimated as being 18.0–74.9 gCO_{2eq} kWh_e^{-1} (mean 45.9) [33,35,36]. Emissions from canal based schemes have been estimated as being 33.9–43.0 gCO_{2eq} kWh_e^{-1} (mean 37.4) [35], while emissions from Dam toe systems have been estimated as 31.2–62.4 gCO_{2eq} kWh_e^{-1} (mean 46.8) [35]. Table 4 shows an overview of estimates of GHG (CO_{2eq}) emissions of hydropower systems.

3.1.4. Marine Technologies (wave power and tidal energy)

Information on the life cycle GHG emissions from wave power is extremely limited. This lack of information reflects the fact that wave power is in its infancy. The Carbon Trust reported life-cycle CO_2 emissions (i.e., not CO_{2eq} and therefore only considers CO_2) for wave power as being in the range 25.0–50.0 gCO_2 kWh_e^{-1} [37]. Parker et al. [38] also reported the GHG emissions associated with recycling and disposal of wave power installations. They reported a mean GHG emission of 22.8 gCO_{2eq} kWh_e^{-1}, with a range of 12.0–39.0 gCO_{2eq} kWh_e^{-1}. Similarly to wave power, information on the life cycle GHG emissions from tidal energy is extremely limited. Again, this lack of information reflects the lack of maturity of this technology. There is some commercial literature that claims that tidal energy provides a net overall saving in GHG emissions, with estimates as low as -20 gCO_{2eq} kWh_e^{-1} under some circumstances [39]. However, these estimates are unlikely to cover the full life cycle of a tidal energy installation, given that recycling and disposal operations have been estimated to produce between 10.0 and 20.0 gCO_{2eq} kWh_e^{-1} (mean of 15.0 gCO_{2eq} kWh_e^{-1}). This highlights some of the uncertainties in reported values, and in many cases a lack of clarity regarding the system boundary used in the

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[1] If the production of a given hydro power plant is entirely seasonal notably for most run-of river plants, the back-up generation of electricity (required to compensate; for example, fossil fuelled back-up)should be included in the assessment (Gagnon and Vate [33]).

Table 6
Overview of GHG emissions (gCO$_{2eq}$) of geothermal.

Study	gCO$_{2eq}$/kWh (Electricity)			Comments
	Mean	Min	Max	
[46]	53	39	78	For a 1.75 MW plant, extracting heat at different depth and efficiencies
[10]	15	11	26	Depends on lifetime and capacity factors
[123]	41			German estimates for hot dry rock system
[129]	18.9			

life cycle analysis. Table 5 shows an overview of estimates of GHG (CO$_{2eq}$) emissions of marine technologies (wave power and tidal energy).

3.1.5. Geothermal

One of the biggest limitations of renewable technologies, especially wind power and solar devices, is the intermittent nature of the resources they use. This leads to variable power output, a relatively low capacity factor, and a higher economic life cycle cost per kWh [40]. In this context, the exploitation of geothermal resources is advantageous [41]. Geothermal technologies are characterised by their reliability, high capacity factor (frequently over 90%; [42]), and constant base-load power [43], thus overcoming the key restriction of intermittent renewable technologies. These factors make conventional geothermal technology one of the cheapest means of producing electricity, with a price of 0.04–0.07 USD kWh^{-1} [44]. Geothermal installed capacity is currently ~10.7 GWe worldwide with 29% located in the United States, 18% in the Philippines, 11% in Indonesia, 9% in Mexico, and 8% in Italy [45]. To date, few LCAs have been performed for geothermal power plants and publications on this topic are quite recent [46]. Overall, the results presented in these studies are consistent. Mean emissions of GHGs from geothermal installations are commonly estimated in the range of 40.0–60.0 gCO$_{2eq}$ kWh$_e^{-1}$, with minimum values around 11.0 gCO$_{2eq}$ kWh$_e^{-1}$ (e.g., Hondo [10]), and maximum estimates around 78.0 gCO$_{2eq}$ kWh$_e^{-1}$ (e.g., Frick et al. [47]). These values are of the same order of magnitude as the majority of other renewable technologies reviewed in this paper. The main sources of GHG emissions from geothermal installations are from the diesel used to drive the electric generating set (~33% of life cycle GHG emissions; [41,47]). Other important sources of life cycle GHG emissions include the embedded GHGs in the pig iron used in the construction of the plant (~10% of life cycle GHG emissions), and a range of lesser sources including the light fuel oil in the industrial furnace, sinter iron at plant, lignite burned in power plant, and natural gas in industrial furnace [47]. Table 6 shows an overview of estimates of GHG (CO$_{2eq}$) emissions of geothermal.

3.1.6. Photovoltaic (PV)

Photovoltaic (PV) electricity is now one of the most promising renewable energy sources. The primary energy source – solar radiation – is practically infinite on the scale of human needs (providing a few thousand kWh m^{-2} y^{-1}, depending on location). Solar PV technology enables direct conversion of sunlight into electricity through semiconductor devices called solar cells, which are interconnected and hermetically sealed to constitute a PV module. The PV modules are integrated with other components such as storage batteries to constitute solar PV systems and power plants that are highly reliable and modular in nature. Ito et al. [48] reported that the conversion modules are currently too inefficient and expensive for large scale deployment. However, the price of PV modules as per MW has fallen by about 60% since 2008 [49] though it is unclear if this reduction is global. Mostly thanks to governmental subsidies, PV is gaining ground in some countries [16,50] with a global installed capacity of 1.5 GW in

2005 [51]. Most of this growth has come from grid connected systems, though the off-grid market has also continued to expand [13]. The high cost of PV cells and associated Balance of System (BOS) are the main barriers to uptake [13,48]. Consequently, there is an intense R&D effort in many countries for the development of new technological solutions to the challenge of converting solar radiation directly into electricity [50]. There are a number of life cycle analyses carried out for solar PV systems, primarily for c-Si and a-Si cells. For c-Si systems, estimates of GHG emissions (gCO$_{2eq}$ kWhe^{-1}) range from 9.4 to 300 (mean 91.1) [10,48,52–55]. For a-Si systems, estimates of GHG emissions (gCO$_{2eq}$ kWhe^{-1}) range from 15.6 to 50.0 (mean 30.5) [10,48,54]. Table 7 shows an overview of estimates of GHG (CO$_{2eq}$) emissions of PV systems.

3.1.7. Solar thermal

Solar thermal electricity generation technologies can be categorised into parabolic trough, central receiver, paraboloidal dish, solar chimney and solar pond. In the parabolic trough solar electricity generation system, the solar receiver consists of a large array of parabolic trough reflectors that reflect the sunlight to a black absorber tube. This tube is cooled by a heat-transferring fluid which, when hot, is pumped to a heat exchanger of a steam Rankine cycle for power generation. In the central receiver solar electricity generation system, the collector consists of two large, two-axis tracked field of mirrors (heliostats), which reflect the beam of radiation to a centrally placed receiver mounted on top of a tower. In the solar chimney electricity generation system, a flat area covered by glass is exposed to the sun. The soil and air underneath the glass cover heats up to around 35 °C above ambient (greenhouse effect). The cover is slightly inclined towards its centre where a large chimney is installed. This allows the hot air to rise up causing wind speed to increase at the entrance to the chimney (draw). This air flow is used for electricity generation by means of a wind turbine [56]. In the paraboloidal dish solar electricity generation system, a paraboloidal dish reflector is used as the solar collector. The heat to electricity conversion is achieved using a stirling engine [57]. A solar pond is usually a large reservoir of water with a black bottom absorbing the solar diffuse and beam radiation and transforming it to heat in the form of hot water [58,59]. There have been a limited number of life cycle analyses looking specifically at solar thermal technologies. Emissions of GHGs (gCO$_{2eq}$ kWhe^{-1}) have been estimated for central receiver systems as between 36.2 and 43 (mean 39.6) [60,61]. A single study into solar chimney technology has estimated GHG emissions as being 202 gCO$_{2eq}$ kWhe^{-1} [62], while emissions from parabolic trough technologies have been estimated as being 196 gCO$_{2eq}$ kWhe^{-1} [62]. Table 8 shows an overview of estimates of GHG (CO$_{2eq}$) emissions of solar thermal.

3.1.8. Dedicated biomass

In terms of life cycle analysis, research into various forms of biomass and bioenergy has been more prolific than for any other form of renewable technology. This probably reflects the wide variety of different systems and technologies available, and the potential of these technologies to integrate into existing

Table 7
Overview of GHG emissions (gCO$_{2eq}$) of photovoltaic.

Study	gCO$_{2eq}$/kWh (electricity)			Comments
	Mean	Min	Max	
[10,47,51,52,54,145]	91.1	9.4	300	For c-Si systems
[51]	217			Only CO$_2$ emissions; based on 2.7 kWp generator
[53]		50	60	Only CO$_2$; current estimate
[53]		10	30	Only CO$_2$; future estimate
[10,47,53]	30.5	15.6	50	For a-Si systems
[122]		20	50	
[133]	88	75	116	UK estimates
[134]		22	49	Average estimates for US
[135]		20	55	Estimates for multi-, mono-Si, Ribbon, CdTe
[136]	38	21	45	
[10]	53	25	136	Rooftop 3 kW PV system (pc-Si) – base case. Depends on lifetime and capacity factors
[10]	43.9	20	111	Rooftop 3 kW PV system (pc-Si) – future case 1. Depends on lifetime and capacity factors
[10]	26	12	66	Rooftop 3 kW PV system (pc-Si) – future case 2. Depends on lifetime and capacity factors
[137]		31	67	Only C emission rate; based on very large scale generators
[130]	79	39	110	Based on LCA for small scale plants (3 kWp)
[123]	104			German estimates for a 3 kW pc-Si system
[138]		48	167	Estimates for pc-Si, CIS, CdTe
[128]	106	53	217	Australian estimates
[129]	49.2			

Table 8
Overview of GHG emissions (gCO$_{2eq}$) of solar thermal.

Study	gCO$_{2eq}$/kWh (Heat)			gCO$_{2eq}$/kWh (Electricity)			Comments
	Mean	Min	Max	Mean	Min	Max	
[59,60]				39.6	36.2	43	
[59]					30	150	
[61]				202			
[61]				196			Estimates for parabolic trough technologies
[123]				14			German estimates for 80 MW parabolic through system
[123]	21.6						German estimates for solar thermal collector

agricultural, forestry and waste management systems. Many biomass to energy technologies are considered to be carbon neutral, thus life cycle analyses are focussed on the agricultural/silvicultural production and processing. This leads to an extremely wide range of life cycle GHG estimates for biomass and bioenergy depending on a whole variety of agricultural, silvicultural and management factors.

Several studies have analysed the environmental impacts of bioenergy and have reported a wide range of results depending on the feedstock used [63], the reference system (e.g., fossil energy production) which is replaced [64], accounting rules and systems boundaries within the life cycle analysis [65], feedstock transport distances [66], and other factors [67]. Accordingly, the estimates of GHG mitigation potentials can vary by over an order of magnitude [67].

In dedicated biomass systems, the biomass comes from areas of land areas dedicated to the growth of the source material. While dedicated crops are grown first and foremost for energy, they may also produce non-energy by-products. When the biomass is burnt to generate electricity, heat is produced as a by-product, which for example can be used for supplying space/water heating.

Biomass use for energy production is often considered in lifecycle calculations to be 'carbon neutral' because combustion of biomass is assumed to release the same amount of CO$_2$ as was captured by the plant during its growth.

However, an important consideration in LCA studies is the contribution to net GHG emissions from N$_2$O (298 CO$_{2eq}$ [68]), which evolves from N fertilizer production and application and organic matter decomposition in soil [69]. Many of the LCA studies included in this review neglected N$_2$O emissions; those that did include them tended to utilise generic emission factors published by the IPCC [70]. In the case of methane, Thustos et al. [71] and Ojima et al. [72] reported that cultivation of agricultural and lignocellulosic crops can limit oxidation of CH$_4$ in aerobic soils, and thereby increase the concentration of CH$_4$ in the atmosphere. This decrease in oxidation is related both to the use of N fertilizer and cultivation type; the reduction in CH$_4$ uptake is equivalent to emission of CH$_4$ from cultivated soils. Such reduction is sensitive to a number of site-specific factors such as soil temperature, soil moisture, and the amount and kind of N fertiliser. As a consequence, measured effective emissions can range over orders of magnitude; for example, CH$_4$ emissions related to fertiliser use can range from effectively zero to in excess of 100 g CH$_4$ kg N^{-1} [73]. However, Delucchi and Lipman [73] also noted that a value of 10 g CH$_4$ kg N^{-1} for CH$_4$ uptake reduction (which corresponds to a tantamount emission of CH$_4$) is reasonable for most circumstances and results in a relatively small contribution to life cycle GHG emissions of the bioenergy chain.

By contrast, CH$_4$ emissions may play a big role if peat soils are involved (although, they are less likely to be cultivated in

Table 9
Overview of GHG emissions (gCO$_{2eq}$) of dedicated biomass.

Study	gCO$_{2eq}$/kWh (Heat)			gCO$_{2eq}$/kWh (Electricity)			Comments
	Mean	Min	Max	Mean	Min	Max	
[62]					75.0	650.0	Depends on feedstock
[65]					31.0	104.0	Only CO$_2$; maize and grass
[66]					100.0	400.0	Cattle slurry and maize
[139]					54.0	108.0	Wood chips and pellets
[140]					45.7	146.5	Reviews studies on different liquid biofuels
[141]	25.2				14.4	28.8	CHP by combusting wood chip (large-scale); gasification of wood chip (small-scale)
[141]					79.2	237.6	Large-scale combustion of various biomass
[141]					25.2	28.8	Gasification of biomass
[141]					50.4	57.6	Pyrolysis of biomass
[123]	28.8	21.6	36		37.0	86.0	German estimates for steam turbine driven by biomass (forest wood, short rotation forest, straw)
[142]				118.0			Review; estimates for biomass plantation
[105]					60.0	270.0	Short-rotation coppice wood chips
[105]					200.0	550.0	Straw as feedstock
[129]				58.0			

comparison to mineral soils) as they represent a large store of C and small losses may have a big influence on GHG balances. Methane emissions to the atmosphere from peat soils depend on the rates of CH$_4$ production and consumption and the ability of the soil and plants to transport the gas to the surface [74]. The major environmental factors that control emission rates from peatland are water table depth, temperature, substrate properties, drainage, and N fertilisation [75]. The majority of work in this area has concentrated on tropical peatlands where cultivation of oil palm for biofuel has significantly increased in recent years [74]. Table 9 shows an overview of estimates of GHG (CO$_{2eq}$) emissions of dedicated biomass.

3.1.9. Energy from waste (waste to energy)

Biomass residues and wastes are materials of biological origin arising as by-products and wastes from agriculture, forestry, forest or agricultural industries, industry, households, etc. [76]. Unlike dedicated bioenergy crops, biowaste and residues are not produced specifically for use as an energy resource. They are the result of economic activity and production of goods in almost all sectors of the economy. Energy from waste or residues, landfill gas or anaerobic digestion is used to generate electricity with heat being produced as a by-product. The technology provides electricity (and heat) at both domestic and industrial scale. As the production of biowastes occurs anyway, the diversion of biowaste to energy recovery options does not usually increase environmental pressures, apart from the following exceptions [77]:

- The removal of forestry or agricultural residues from land can reduce carbon storage and carbon pools like soil, dead wood or litter, and can deplete soil nutrients.
- The creation of a market for biomass residues or by-products, giving an additional income stream, can make the production of the main commodity (such as timber) economically more attractive, leading to an expansion of this land use, which may have negative environmental impacts (e.g., if native forests are replaced). However, increased production of wood products may also have positive climatic impacts through substitution of more emission intensive materials.

The diversion of biowaste away from landfill to energy recovery can also alleviate some of the environmental pressures associated with landfill, such as methane emissions from anaerobic decomposition of biomass in landfill.

In the UK, anaerobic digestion (AD) is viewed as one of the most economic and technically appropriate methods for treating biodegradable municipal wastes such as source segregated food waste [78]. Within the EU-27, agriculture is the third most significant source of GHG emissions after the energy sector and industrial processes, thus farm-scale AD has the potential to play a significant role in promoting sustainable development and reducing anthropogenic GHG emissions [79]. As a sustainable environmental technology, AD is viewed as being attractive to the agricultural sector as it stabilises the organic wastes (e.g., manure) and produces renewable energy in the form of biogas (CH$_4$ and CO$_2$) and a reasonably nutrient rich digestate. The produced CO$_2$ neutral biogas can be used to replace fossil fuels for heat and/or electricity generation, and/or can be upgraded to vehicle fuel. The choice of whether to utilise biogas for electricity and heat generation, or upgrading the biogas to biomethane for transport fuel use or injection to the gas grid, is largely an economic decision or in many cases influenced by specific site restrictions. As AD is performed mainly in sealed containers/reactors, the produced biogas can be recovered and GHG emissions due to manure management can be avoided to a large extent. If sufficient quantities of electricity and heat are produced, farms can become energy self-sufficient or even become a net energy producer. In addition, AD may destroy some pathogens, control odours (depending on the feedstock(s) and alternative feed stock handling operations available), and the use of digestate as a fertilizer may improve soil quality through recirculation of the nutrients conserved during the AD process [80]. This in turn reduces eutrophication and also fossil energy consumption in the production and consumption of inorganic fertilizers [81]. Finally, the GHG emissions from the use of the digestate on agricultural soil should also be low as most of the organic compounds are decomposed during the AD process [82]. Anaerobic digestion of manures has been extensively studied (e.g., see reviews by Holm-Nielsen et al. [83] and Cantrell et al. [84]) and also increasingly implemented in countries such as Germany, Austria and Denmark [79]. In 2007, there were more than 4000 agricultural biogas plants in the EU, with 3750 of these in Germany alone [85]. Increasingly stakeholders are requesting guidance on the environmental costs and benefits of the various infrastructure options open to them [78]. There are a large number of LCA studies that have evaluated the various biogas infrastructure options. However, many of the studies involving life cycle approaches to assessing or comparing biogas systems concentrate on energy balances [86,87] or a combination of energy balance and emissions [64,88]. As highlighted by Pöschl [86] studies also tend to focus on either specific feedstocks [89,90], specific biogas technologies [91,92], waste management strategies at various geographic scales [77,93] or specific biogas end uses [65]. This wide variability in both scope

Table 10
Overview of GHG emissions (gCO_{2eq}) from waste treatment.

Study	gCO_{2eq}/kWh (electricity)			Comments
	Mean	Min	Max	
[123]	37.0			German estimates for steam turbine driven by waste wood
[146]	330.0			
[143]		97.2	144.0	Emission factors for waste incineration in units of kg fossil CO_2 per GJ energy content in waste.
[144]	830.0	168.0	1000.0	Calculated from (the non-biogenic) CO_2 emissions (ca. 415 kg CO_2/ton MSW) and electricity production from MSW incineration (ca. 500 kWhe/ton MSW)

and approach makes the interpretation of the various results difficult [94]. Table 10 shows an overview of estimates of GHG (CO_{2eq}) emissions of waste treatment technologies.

3.1.10. Heat pumps

Heat pumps use electricity (i.e., high-grade energy) to extract heat (i.e., low-grade energy) from the external environment and through a compression system produce heat for space and/or water heating, mainly at domestic scale. Heat pumps can use air (ASHP), the ground (GSHP) and water (WSHP) as an external source of heat. Although heat pumps rely on electricity to operate, their high co-efficient of performance (COP) means they extract more heat energy from the environment than they use in electricity. In general, most of the energy for heating with heat pumps comes from the external environment, and only a fraction comes from the high-grade energy source. The heat power released from an electrically powered heat pump to a building can be typically two or three times larger than the electrical power consumed, corresponding to a system efficiency of 200–300%, as opposed to the 100% efficiency of a conventional electrical heater, in which all heat is produced from input electrical energy. If the electricity used to run the heat pumps is generated from a renewable source, heat pumps can be considered to provide renewable heat.

Geothermal heat pumps (GHPs) have evolved as an attractive technology for space heating and cooling. It is predicted that worldwide the use of such systems will exponentially increase in the next few decades [95,96]. GHPs utilise the underground environment as a free geothermal energy reservoir or storage medium and thus can be applied nearly everywhere, even in areas of low geothermal gradient [97]. In open systems, such as groundwater heat pump systems, wells are installed and groundwater is used directly as the heat carrier. However, much more common are closed systems (ground source heat pumps; GSHPs), where boreholes (typically < 400 m in depth) are equipped with pipes that act as borehole heat exchangers. Energy transfer between the borehole heat exchangers and the ground is established by circulating a synthetic heat carrier fluid. Alternatively, the pipes can be laid flat within the soil which negates the need to drill boreholes. However this requires a significant land area in order to lay ~ 400 m of pipe in a horizontal formation. So far only a few studies have investigated the life cycle impacts of domestic heat pumps. Greening and Azapagic [98] compare estimates of the environmental life cycle impact from three types of domestic heat pumps (ASHP, GSHP and WSHP) in the UK with gas boilers. They find that heat pumps on average have 70–80% higher environmental impacts than gas boilers due to the use of electricity. However, in terms of life-cycle GHG emissions (the global warming potential) the heat pumps have lower impacts than the boilers, with GSHP and WSHP having the lowest GHG emissions (189 gCO_{2eq} kWh^{-1}), while ASHP have higher emissions (276 gCO_{2eq} kWh^{-1}) due to lower efficiencies and higher material requirements for the system. Lo Russo et al. [99] calculated significant potential savings in

energy use and CO_{2eq} emissions as a main argument for using low-enthalpy geothermal technologies for space heating/cooling. Blum et al. [100] studied the total CO_{2eq} savings of vertical GSHP systems in South Germany. They concluded that the minimum resulting CO_{2eq} savings for one installed GSHP unit is about 1800 kg CO_{2eq} yr^{-1} (equates to roughly 65.0–149 gCO_{2eq} kWh$_e^{-1}$) compared to the average CO_{2eq} emission from the German electricity mix. Calculated life cycle GHG emissions depend on (hydro) geological conditions, technology and technological design, (time-dependent) heating/cooling requirements, CO_{2eq} intensity of primary energy for running the heat pump, as well as the available alternative heating/cooling system. The primary energy used for running the heat pump is a key consideration. Greening and Azapagic [98] estimated GHG emissions from GSHP installations to be as low as 90.0 gCO_{2eq} kWh$_e^{-1}$ assuming an electricity mix based on 80% renewables. This estimate rises to 189 gCO_{2eq} kWh$_e^{-1}$ based on the current electricity mix. The same authors provide similar estimates for air source heat pumps (138 gCO_{2eq} kWh$_e^{-1}$ for an electricity mix based on 80% renewables; 27 gCO_{2eq} kWh$_e^{-1}$ for the current electricity mix). The efficiency of the heat pump is another important factor affecting the GHG emissions. For example, Johnson [101] finds that increasing CoP from 2.9 to 3.9 reduces emissions from ASHP from 260 to 210 kg CO_{2eq}/kWh. Table 11 shows an overview of estimates of GHG (CO_{2eq}) emissions of heat pumps.

4. Discussion

This article reviewed 79 LCA studies directly related to the greenhouse gas emissions of renewable energy technologies. In the following sections, key elements influencing the results of the LCA studies in the previous section are identified. These include life cycle stages, the system boundaries, context of the studies and the resulting functional units. The remainder of this section will discuss LCA impacts included in the studies, comparison with conventional systems and previously reported estimates.

4.1. Key elements

Life cycle analyses of RETs focus on the sequence of fuel extraction, transportation, treatment, conversion, transmission and distribution, waste disposal and dismantling of the facility [102]. Fig. 2 shows the main life cycle components upstream, production and downstream for electricity or heat supply systems. The proportion of GHG emissions from each life cycle stage differs by technology. For RETs, the majority of GHG emissions occur upstream of operation [103]. Upstream processes potentially having relevant impacts include fuel provision and the commissioning and decommissioning of plants. For fossil-fuelled technologies, fuel combustion during operation of the facility emits the vast majority of GHGs ($\sim 83\%$) [103]. However, fuel provision is the main factor responsible for GHG emissions for biomass ($\sim 71\%$) [104] while infrastructure represents the nearly exclusive burden

Table 11
Overview of GHG emissions (gCO$_{2eq}$) from heat pumps.

Study	gCO$_{2eq}$/kWh (heat)			Comments
	Mean	**Min**	**Max**	
[100]	207	150	264	For ASHP using different efficiencies
[97]	276	138	276	ASHP. Lower values is for an electricity mix based on 80% contribution from renewables
[97]	189	90	189	GSHP and WSHP. Lower values is for an electricity mix based on 80% contribution from renewables
[99]		65	149	German estimates for GSHP for different electricity mix (national and regional)
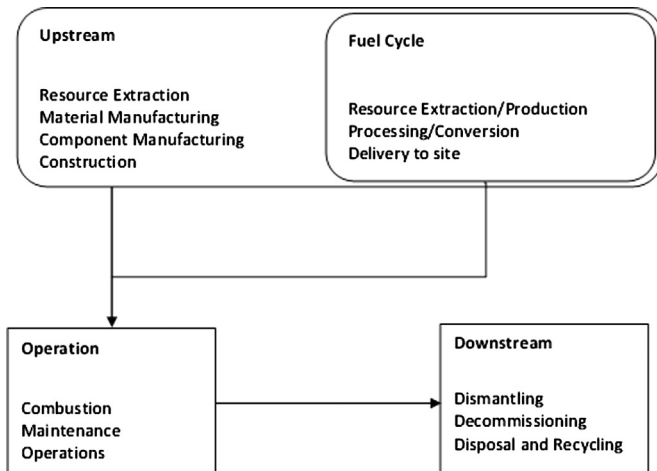
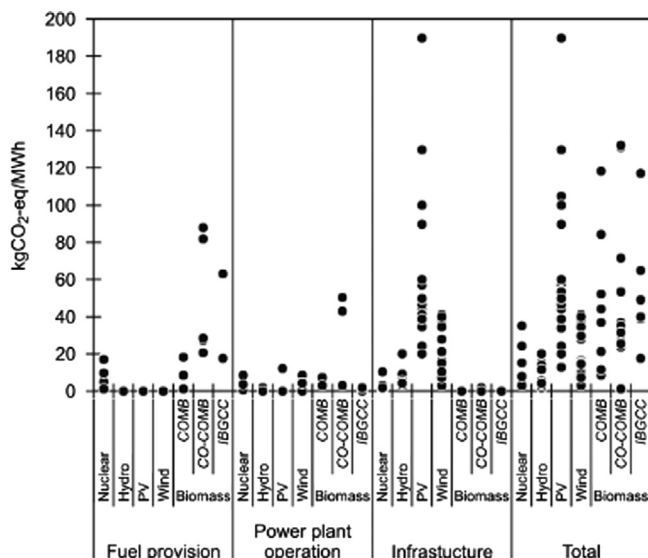**Fig. 2.** Main life cycle components for electricity/heat supply systems.

Fig. 3. Life cycle GHG emissions from selected technologies, divided into "fuel provision", "plant operation" and "infrastructure", according to [104].

(97–99%) of total GHG emissions for hydropower, PV and wind systems (Fig. 3). Most studies in our review did consider all life cycle stages to some degree. The stages that were covered least included raw material acquisition (including fuel extraction), manufacturing, and transportation. One major contributing factor to the lack of coverage of these stages is difficulty in collecting and validating data. Most of the studies which cover life cycle stages extensively fail to provide adequate information about data sources. It is the view of the authors that whilst some commercial LCA software tools make data inventory easier, it is not always clear how data is processed within these tools. However, authors agree with Curran [105] that there have been some success in this

area. For example, through efforts such as the EcoInvent database and the European Commission's platform on Life Cycle Assessment, creating publicly available databases.

Generally, a well-defined context (goal) within which a study is conducted simplifies the study boundaries and helps setting the functional unit for the study. The results from our review suggest that when it comes to functional units, the norm is to use CO$_2$ equivalents per unit hour (kWh, MWh, etc.) of electricity produced. However, we identified significant differences in defining system boundaries. This poses significant challenges to the comparisons of greenhouse gas emissions, as, the results in the previous section clearly show the importance of correctly setting and communicating system boundaries.

4.2. Potential life cycle Impacts of electricity and heat generation from RETs

This article specifically reviews Life cycle greenhouse gas estimates. However, there are many other life cycle impacts of electricity and heat generation beyond the emission of greenhouse gases. In addition to NH$_3$, emissions of NO$_x$ and SO$_2$ are largely responsible for acidification (SO$_2$, NO$_x$ and NH$_3$) and eutrophication (NO$_x$ and NH$_3$). Because NH$_3$ is primarily emitted from animal waste in agriculture, NO$_x$ and SO$_2$ emissions provide a reasonable approximation for contributions to acidification and eutrophication due to electricity and heat generation [104]. Also, most energy technologies have substantial land requirements when the whole supply chain is included. However, literature reporting lifecycle estimates for land use by energy technologies is scarce [103]. The limited evidence available suggests that lifecycle land use by fossil energy chains can be comparable and higher than land use by Renewable energy sources [106,107]. Closely connected to land use are (site specific) impacts on ecosystems and biodiversity. According to Sathaye et al. [103], the assessment of impacts on biodiversity are not part of LCA methodologies, and even though efforts are made to establish and integrate indicators into the context of LCA (e.g., [108]), no framework for the comparison of lifecycle impacts of different energy chains is currently available. Moreover, LCA assesses a wider range of environmental impacts, such as the production of particulates or requirements for water, etc. Water use in upstream processes can be high for some energy technologies, particularly for fuel extraction and biomass feedstock production [107]. As Curran [105] points out, the interpretation phase of LCA entails the evaluation of the results of the inventory analysis along with the results of the impact assessment to aid in the decision making process whether it is to select the preferred raw material or compare different renewable energy technologies in this case. However, although GHG emissions are an adequate indicator of the environmental performance regarding global warming, other environmental impacts should also be considered. Life cycle assessment publications that intended to differentiate products based on their environmental impacts generally focused on three or four main impacts instead of presenting an end-result-weighted score or a more complete set of impacts [109]. Even before scaling down the references in our review, excluding
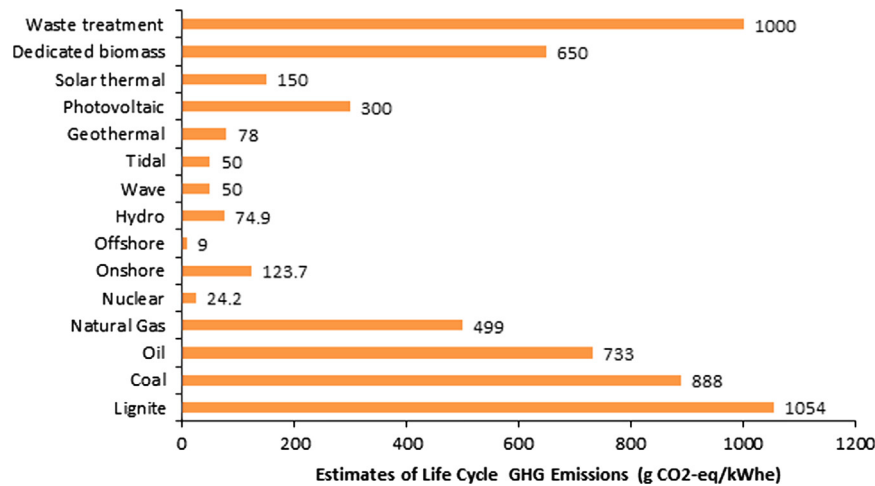
Fig. 4. Maximum GHG emission levels of electricity generation methods.
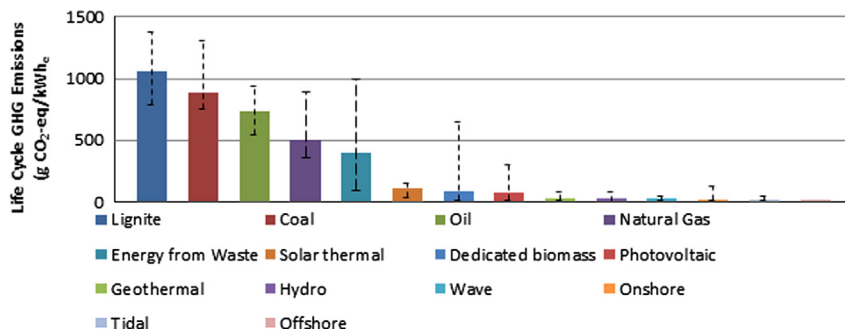

Fig. 5. Life cycle GHG emission estimates of electricity generation methods.

energy use, global warming (GHG emissions) was the leading impact category in most of the studies. This is likely due to the importance placed on GHG emissions in recent years [110] and the objective of renewable technologies to replace them. Of the 85 studies reviewed, 55 assessed emissions of all three compounds: GHG, NO_x and SO_2. 22 Studies provided NO_x and SO_2 emission data disaggregated according to the individual life cycle stage. Here, authors agree with Bousquin et al. [110], that the danger in limiting impact categories to a handful is that their impacts have to be normalised to determine significance relative to one another. For example, the impact on human toxicity may be small in comparison to GHG emissions, but the visibility of this impact may be such that its weight is greater to the communities affected by it. It is in fact the view of authors that emissions data for other important categories, where available, should be included in assessments.

4.3. Comparison with conventional systems

Fig. 4 shows comparison between renewable electricity generation technologies (RETs) and the conventional electricity generation sources. Data used in Fig. 4 represents the worst case scenarios (maximum emission values) for renewable energy technologies from sources of this review and average values for conventional fuel sources. The life cycle emissions (CO_2 emission factors) are comparatively higher in conventional sources as compared to renewable sources. Nuclear-based power electricity generation however has fewer emissions to the environment but the disposal of the radioactive material causes greater environmental impact to the surroundings [13]. The only exceptions here are waste treatment and dedicated biomass technologies (DBTs) which could have potentially high GHG emissions based on the

feedstock and the inputs required for their production. The significant diversity of bioenergy (dedicated biomass or waste) options and methods of production gives rise to wide variation in carbon footprints. Some research studies have found that the carbon footprint of electricity from bioenergy is generally, but not always lower than that of the least carbon intensive fossil-fuel option, gas-fired combined cycle gas turbines (CCGTs) [111,112]. For example, electricity generated through combustion of short-rotation coppice wood chips has an estimated carbon footprint of 60–270 gCO_{2eq}/kWh, which in all cases is below the lowest UK CCGT figure of 365 gCO_{2eq}/kWh. For straw, however, footprints range from 200 to 550 gCO_2eq/kWh [112]. Authors agree that the greenhouse gas emissions of conventional systems such as fossil fuelled power plants could decrease with the installation of a CO_2 removal facility but the life cycle effects (installation and operation) of the removal facility must be taken into account (Fig. 5).

4.4. Comparison to previously reported results

The Intergovernmental Panel on Climate Change (IPCC) in 2011 aggregated and harmonised the CO_2 emission findings of hundreds of papers, which were published between 1980 and 2010 [113]. In 2011 the Committee on Climate Change (CCC) of the UK Houses of Parliament was presented a report based on estimates including more than 30 peer-reviewed studies outlining the carbon footprints of a variety of electricity generation technologies [114]. These reported results were compared to the findings from this study as summarised in Table 12. Values presented from the IPCC study indicate estimated median values, whilst values from the UK report and this study are presented in ranges of minimum and maximum. The results appear to indicate that aside GHG emissions for electricity generated from wave and tidal

Table 12
Reported GHG estimates for RETs (IPCC, UK and this study).

Renewable energy technology (RET)	Life cycle GHG estimates (gCO_2-eq/kWh_e)		
	IPCC	UK	This study
Wind – Onshore	12	20–96	8–124
Wind – Offshore	–	–	5–24
Hydro	4	–	2–75
Wave	–	12–39	12–50
Tidal	–	10–20	10–50
Geothermal	45	–	11–78
Photovoltaic	46	–	9–300
Solar thermal	22	75–116	30–150
Dedicated biomass	18	25–550	14–650
Waste treatment	–	–	97–1000

technologies in the UK whose ranges correspond to the results of this study, wind (onshore), solar thermal and dedicated biomass all fall short from the estimated minimum values of this study and significantly more than the estimated averages of the IPCC reported values. Authors would however like to state that estimated GHG emission values are sensitive to factors including the technology's operating conditions and country of its manufacture, etc. and as such, comparing GHG estimates must be done with extreme caution. Notwithstanding, such comparisons are important to motivate system improvement.

5. Scope of review

The broad goal of this study is to present current estimates of life cycle GHG emissions from a range of renewable electricity and heat technologies to better inform decision making and future analyses where such estimates would be useful. This review is limited to the level of detail that is provided on the models and data used in the LCA study. However, to provide a more comprehensive perspective of the environmental and social impacts of renewable electricity and heat technologies, other technical parameters such as capacity factors, operating lifetime, performance ratio, etc. and system parameters such as human health impacts, water consumption, jobs created, etc., as discussed in previous sections should also be assessed.

6. Opportunities for the future

This study has shown that life cycle analysis is an effective tool for assessing environmental impacts of renewable energy technologies, including estimation of GHG emissions. However, LCA is a data-intensive exercise. The quality of the data has a significant impact on the credibility of the modelling output [115–117]. Therefore, inaccurate data, gaps in data, and unrepresentative data which are often all sources of uncertainty in LCA must be dealt with appropriately [118]. Authors recommend that future studies involving LCA modelling of electricity and heat generation from renewable energy technologies include clear statements of data sources, assumptions and applicability. This represents a research opportunity to develop guidelines for the identification of principal assumptions and parameters that contribute to reduction of uncertainty, harmonisation and transparency of results without compromising on flexibility. In the midst of these challenges, there are also several opportunities to further apply the LCA tool to this important and rapidly growing area of concern.

7. Concluding remarks

This article reviewed 79 recent LCA studies directly related to the life cycle GHG emissions from a range of renewable electricity and heat technologies and provides the GHG emission estimates from the different studies. The review has shown that the lowest GHG emissions were associated with offshore wind technologies (mean life cycle GHG emissions could be 5.3 to 13 gCO_2-eq/kWh). However, energy from waste (waste to energy) and dedicated biomass technologies (DBTs) were found to potentially have high GHG emissions based on the feedstock, selected boundary and the inputs required for their production (97.2–1000 gCO_2-eq/kWh; 14.4–650.0 gCO_2-eq/kWh respectively). The review further demonstrates the variability of existing LCA GHG emission estimates for electricity and heat generation from renewable energy technologies. While some of these differences may reflect actual differences in GHG emissions, others may largely be due to assumptions and other modelling choices. This offers areas for improvement and opportunities for standardisation. The results of this review can provide suitable baseline estimates for future projects in developing renewable energy technologies for electricity and heat production.

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